Analysis of Subthreshold Antiproton Production in p-Nucleus and Nucleus-Nucleus Collisions in the RBUU Approach †

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Abstract

We calculate the subthreshold production of antiprotons in the Lorentz-covariant RBUU approach employing a weighted testparticle method to treat the antiproton propagation and absorption nonperturbatively. We find that the antiproton differential cross sections are highly sensitive to the baryon and antiproton selfenergies in the dense baryonic environment. Adopting the baryon scalar and vector selfenergies from the empirical optical potential for proton-nucleus elastic scattering and from Dirac-Brueckner calculations at higher density $\rho > \rho_0$ we examine the differential antiproton spectra as a function of the antiproton selfenergy. A detailed comparison with the available experimental data for p-nucleus and nucleus-nucleus reactions shows that the antiproton feels a moderately attractive mean-field at normal nuclear matter density ρ_0 which is in line with a dispersive potential extracted from the free annihilation cross section.

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I. INTRODUCTION

The production of particles at energies below the free nucleon-nucleon threshold ('subthreshold production') constitutes one of the most promising sources of information about the properties of nuclear matter at high densities since the particles are produced predominantly during the compressed stage at high density [1–4]. Antiproton production at energies of a few GeV/u is the most extreme subthreshold production process and has been observed in proton-nucleus collisions already more than 20 years ago [5–7]. Experiments at the JINR [8] and at the BEVALAC [9,10] have provided, furthermore, first measurements of subthreshold antiproton production in nucleus-nucleus collisions. Since then the problem was taken up again at KEK [11] and GSI [12] with new detector setups. Various descriptions for these data have been proposed. Based on thermal models it has been suggested that the antiproton yield contains large contributions from $\Delta N \rightarrow \bar{p} + X$, $\Delta\Delta \rightarrow \bar{p} + X$ and $\rho\rho \rightarrow \bar{p}N$ production mechanisms [13–15]. Other models have attempted to explain these data in terms of multiparticle interactions [16].

In a first chance nucleon-nucleon collision model (assuming high momentum tails consistent with data on backward proton scattering) Shor et al. [17] succeeded in reproducing the antiproton yield for the proton-nucleus case; however, these authors underestimated the yield by more than 3 orders of magnitude for nucleus-nucleus collisions. This problem was partly resolved by Batko et al. [18] who performed the first nonequilibrium $\bar{p}$-production study on the basis of the VUU transport equation. Essential for this success was that in A + A reactions the dominant production channel proceeds via an intermediate nucleon resonance which allows to store a sizeable amount of energy that can be used in a subsequent collision for the production of a $p\bar{p}$ pair. Later on, these findings were also confirmed by Huang et al. [19].

These results have led to the suggestion that the quasi-particle properties of the nucleons might be important for the $\bar{p}$ production process which become more significant with increasing nuclear density. Schaffner et al. [20] found in a static thermal relativistic model,

assuming kinetic and chemical equilibrium, that the $\bar{p}$-abundancy might be dramatically enhanced when assuming the antiproton selfenergy to be given by charge conjugation of the nucleon selfenergy. This leads to strong attractive vector selfenergies for the antiprotons. However, the above concept lacks unitarity between real and imaginary part of the $\bar{p}$-selfenergy and thus remains questionable. Besides this, even in the $\sigma - \omega$-model the Fock terms lead to a suppression of the attractive $\bar{p}$-field [21], such that the production threshold is shifted up in energy again as compared to the simple model involving charge conjugation. Furthermore, the assumption of thermal and especially chemical equilibrium most likely is not fullfilled e.g. in $Si + Si$ collisons around 2 GeV/u [22].

First preliminary results of a fully relativistic transport calculation for antiproton production including $\bar{p}$ annihilation as well as the change of the quasi-particle properties in the medium have been reported in [23]. There it was found that according to the reduced nucleon mass in the medium the threshold for $\bar{p}$-production is shifted to lower energy and the antiproton cross section prior to annihilation becomes enhanced for $Si + Si$ at 2.1 GeV/u by approximately a factor 70 as compared to a relativistic cascade calculation where no in-medium effects are incorporated. However, all these transport calculations [18,19,23] suffered from an approximate geometrical treatment of the very strong annihilation channel and a neglect of the momentum dependence of the baryon selfenergies.

In our present work we therefore analyze the production of antiprotons in the framework of the relativistic transport theory (RBUU) where antiprotons are propagated explicitly in the respective time dependent potentials and their annihilation is calculated nonperturbatively by means of individual rate equations.

First results have been published in [24]. Results of a very similar investigation by Li et al. [25] have recently become available and we compare frequently with the outcome of this study.

In this respect we first discuss two simple models for the $\bar{p}$ selfenergy in section 2 and present the general transport equations for nucleons and antinucleons in section 3. The numerical implementation of $\bar{p}$ production is presented in section 4 as well as a detailed

analysis of the production process with respect to the selfenergies employed, the systematics with respect to projectile and target masses and the individual baryonic production channels. In section 5 we present the treatment of $\bar{p}$ propagation and annihilation and discuss the geometrical aspects of $\bar{p}$ absorption. The explicit comparison of our calculations with the available experimental data for $p + A$ and $A + A$ reactions is performed in section 6, while a summary on the $\bar{p}$ selfenergies concludes the paper in section 7.

II. MODELS FOR THE ANTIPROTON SELFENERGY

The dynamics and the properties of particles in a many-body system strongly depend on their mutual interactions with the surrounding particles and are reflected in their selfenergies. While the real part of the selfenergy describes the change of the particle momenta in the medium, all inelastic reaction channels as well as elastic scattering processes are accounted for by the imaginary part of the selfenergy $\Sigma(p_\mu, \rho_s, j_\mu)$. If the selfenergy Σ is an analytic function of the particle energy $\epsilon = p_0$ its imaginary and real part are related up to a constant by the dispersion relations:

$$Re\,[\Sigma(\epsilon)] = \frac{1}{\pi} P \int_0^{+\infty} \frac{Im\,[\Sigma\,(\epsilon')]}{\epsilon' - \epsilon} d\epsilon' \qquad (1)$$

$$Im\,[\Sigma(\epsilon)] = -\frac{1}{\pi} P \int_0^{+\infty} \frac{Re\,[\Sigma\,(\epsilon')]}{\epsilon' - \epsilon} d\epsilon'. \qquad (2)$$

Since we assume particles and antiparticles to be different particle species the integration in the Principal-value integrals (1) and (2) extends only over positive energies.

In the relevant energy regime (1 - 5 GeV/u) of heavy-ion collisions and proton-nucleus collisions the selfenergies of baryons and antiprotons are known to be quite different. The $\bar{p}$-selfenergy is dominated by the antiproton annihilation with baryons ($\bar{p} + B \rightarrow X$) as shown by low energy antiproton-nucleon scattering experiments at LEAR [26,27]. Since the antiproton production probability at subthreshold energies is extremly low the number of antiprotons produced in heavy-ion collisions and proton-nucleus collisions is negligible compared to the number of baryons involved in the reaction. Thus contributions from

elastic $\bar{p}$-$\bar{p}$-scattering to the antiproton selfenergy can be neglected as well as contributions of $\bar{p}$-annihilation channels to the baryon selfenergies .

A. A dispersive model

In the following we present a simple model for the real part of the $\bar{p}$-selfenergy using the dispersion relation (1). In the low density limit the imaginary part of the selfenergy (neglecting elastic scattering) is given by the integral :

$$2\, Im\, \Sigma_{\bar{p}}(x,\, \Pi_{\bar{p}}) = -\frac{4}{(2\pi)^3} \int d^3\Pi_B\, \frac{m_B^\star}{\Pi_B^0} W(\Pi_{\bar{p}}^\mu, \Pi_B^\mu) f(x, \Pi_B) \tag{3}$$

where $W(\Pi_{\bar{p}}^\mu, \Pi_B^\mu)$ is the probability of an antiproton with momentum $\Pi_{\bar{p}}^\mu$ to annihilate in a collision with a baryon of effective mass $m^\star$ and momentum Π_B^μ. $f(x, \Pi_B)$ is the baryon phase-space distribution function at space-time x whereas the factor 4 in formula (3) arises from the summation over the spin- and isospin-degrees of freedom. We simplify this expression by considering an antiproton moving in infinite nuclear matter of density ρ_0 ($= 0.171/fm^3$) at rest, i.e. $\vec{\Pi}_B = 0$. Both the antiprotons and the baryons now are supposed to have effective masses equal to the restmass of the nucleon. This leads to the following analytic expression for the $\bar{p}$-annihilation probability

$$W(\Pi_{\bar{p}}^\mu, \Pi_B^\mu) = \frac{\sqrt{\Pi_{\bar{p}}^{0\,2} - m_N^2}}{\Pi_{\bar{p}}^0} \cdot \sigma_{abs}(\Pi_{\bar{p}}^0) \tag{4}$$

where σ_{abs} is the total $\bar{p}$-annihilation cross section. Due to the above assumptions the integral over the baryon phase-space distribution function and the summation over the spin- and isospin-degrees of freedom in eq. (3) can be replaced by a multiplication of the annihilation probability with ρ_0. The expression for the imaginary part of the antiproton selfenergy as a function of the antiproton energy then reads

$$Im\, \Sigma_{\bar{p}}(\Pi_{\bar{p}}^0) = -\frac{1}{2} \frac{\sqrt{\Pi_{\bar{p}}^{0\,2} - m_N^2}}{\Pi_{\bar{p}}^0} \cdot \sigma_{abs}(\Pi_{\bar{p}}^0)\, \rho_0 \tag{5}$$

and the real part of Σ at density ρ_0 can be calculated from eq. (3) by employing the dispersion relation (1). We expect this expression to give a reasonable description of $Im\Sigma_{\bar{p}}$ at least for densities up to ρ_0 where possible medium corrections to σ_{abs} are still small.

In order to estimate $Re\Sigma(\epsilon)$ at ρ_0 we adopt the parametrization from [13] for σ_{abs}, i.e.

$$\sigma_{abs} = \sigma_0 \frac{s_0}{s} \left(\frac{A^2\, s_0}{(s - s_0)^2 + A^2\, s_0} + B \right) \tag{6}$$

with the constants $\sigma_0 = 120\, mb$, A = 50 MeV, B = 0.6 and $s_0 = 4m_N^2$. Fig. 1 displays this parametrization in comparison to the experimental data for the free cross section taken from [28] as a function of $s - s_0$ where s is the invariant energy squared. The result of this calculation for $Re\Sigma(\epsilon)$ is displayed in fig. 2 as a function of the $\bar{p}$-kinetic energy. In order to investigate the sensitivity of this result to the parametrization of the absorption cross section we used in addition different parameters B (cf. fig. 2) to vary the overall size of σ_{abs}. For an antiproton at rest we find values for the real part of the selfenergy of -175 MeV up to -100 MeV. While we observe a steep rise for small kinetic energies this flattens out for higher energies and reaches an asymptotic value of 0 - -10 MeV. Furthermore, the variation in the cross section mainly affects the low energy regime. The $\bar{p}$-selfenergies obtained in the framework of this simple model are well in line with the potential analysis for $\bar{p}$+ A reactions by Janouin et al [29].

B. Mean-field models

We now turn to the treatment of the antiproton selfenergies in mean-field models where the imaginary part of the selfenergies is not included at all thus inherently violating the dispersion relations (1, 2).

As an example we consider the mean-field approximation of the familiar $\sigma-\omega$-model [30] where only momentum independent vector $U_v^\mu(x)$ and scalar parts $U_s(x)$ of the selfenergies are taken into account. The equation of motion for a fermion spinor then reads

$$\left\{ \gamma^\mu \left(i\partial_\mu - U_\mu^v(x) \right) - (m + U^s\,(x)) \right\} \Psi\,(x) = 0 \tag{7}$$

while the equation of motion for antiparticles is obtained by applying the charge conjugation operator to this equation. As a consequence the scalar part of the selfenergy is the same

for particles and antiparticles while the vector part of the antiparticle potential changes the sign

$$U_{C\,\mu}^{v}\,(x) \;= -U_{\mu}^{v}\,(x) \tag{8}$$

$$U_{C}^{s}\,(x) \;= U^{s}\,(x)\,. \tag{9}$$

The combination of both parts of the antiparticle selfenergy to the Schrˇdinger-equivalent potential in the non-relativistic limit leads to a strongly attractive potential for the antiprotons when using the original coupling constants from [30]. The value of the Schrödinger-equivalent potential at $\rho = \rho_0$ is approximately -700 MeV for $\epsilon = 0$ and becomes even more attractive with increasing kinetic energy of the antiproton (-1300 MeV for $\epsilon = 2000$ MeV).

A comparison of the results for the Schrˇdinger-equivalent potential obtained in the framework of the $\sigma - \omega$ model and the real part of the $\bar{p}$-selfenergy resulting from the dispersive approach shows strong differences not only in the absolute values but also in their opposite behaviour as a function of the kinetic energy. The fact that the real part of the antiproton selfenergy cannot be described consistently within different models urges us to treat it as a free parameter in our transport model. We regard the determination of this parameter in comparison with the experimental data as the central goal of our work.

III. THE RBUU TRANSPORT APPROACH

In this section we give a brief description of the RBUU-model. First we summarize the relevant equations determining the dynamics of baryons and then describe the implementation of antiprotons in our approach.

A. Baryon dynamics

Since the covariant BUU approach has been extensively discussed in the reviews [31,32] and in [33] we only recall the basic equations and the corresponding quasi-particle properties that are relevant for a proper understanding of the results reported in this study. The

relativistic BUU (RBUU) equation with momentum-dependent mean-fields or selfenergies is given by (for details see refs. [31–33])

$$\{[\Pi_\mu - \Pi_\nu(\partial^p_\mu U^\nu) + m^\star(\partial^p_\mu U_s)]\partial^\mu_x + [-\Pi_\nu(\partial^x_\mu U^\nu) + m^\star(\partial^x_\mu U_s)]\partial^\mu_p\} f(x,p) = I_{coll}, \tag{10}$$

where $f(x,p)$ is the Lorentz covariant phase-space distribution function, I_{coll} is a collision term (cf. eq. (20)), and U_s and U_μ are the scalar- and the vector- selfenergies. The effective mass M^* and the kinetic momentum Π_μ are defined in terms of the fields by

$$\Pi_\mu(x,p) = p_\mu - U_\mu(x,p) \tag{11}$$

$$m^\star(x,p) = m + U_s(x,p) \tag{12}$$

$$\tag{13}$$

while the quasi-particle mass-shell constraint is obtained as

$$V(x,p)\, f(x,p) = 0 \tag{14}$$

with the pseudo potential

$$V(x,p) \equiv \frac{1}{2}\{\Pi^2(x,p) - m^{*2}(x,p)\}. \tag{15}$$

The above equation implies that the phase-space distribution function $f(x,p)$ is nonvanishing only on the hypersurface in phase-space defined by $V(x,p) = 0$.

In order to implement proper selfenergies for the nucleons in line with elastic proton-nucleus scattering we follow ref. [33] and separate the mean-fields into a local part and an explicit momentum-dependent part, i.e.

$$U_s(x,p) = U_s^H(x) + U_s^{MD}(x,p) \tag{16}$$

$$U_\mu(x,p) = U_\mu^H(x) + U_\mu^{MD}(x,p), \tag{17}$$

where the local mean-fields are determined by the usual Hartree equation

$$
\begin{aligned}
U_s^H(x) &= -g_s \sigma_H(x) \\
U_\mu^H(x) &= g_v \omega_\mu^H(x)
\end{aligned} \tag{18}
$$

with

$$
\begin{aligned}
m_s^2 \sigma_H(x) + B_s \sigma_H^2(x) + C_s \sigma_H^3(x) &= g_s \rho_s(x) \\
m_v^2 \omega_\mu^H(x) &= g_v j_\mu(x).
\end{aligned} \tag{19}
$$

In the above equations the scalar density $\rho_s(x)$ and the baryon current $j_\mu(x)$ are given in terms of momentum integrals over the phase-space distribution function (cf. [33–35]). The potentials (17) and (16) correct the unphysical strong repulsion in the $p + A$ and $A + A$ potentials at high erngergies, obtained in the original Walecka model. Refs. [33,34] give parametrizations which describe both the experimental data and the density-dependence obtained in Brueckner-calculations very well.

Now we turn to the discussion of the collision term I_{coll} describing the baryon-baryon collisions (cf. [1,31,36]):

$$
\begin{aligned}
I_{coll} = \frac{4}{(2\pi)^5} \int & d^3\Pi_1 \, d^3\Pi_1' \, d^3\Pi' \frac{m^\star \, m_1^\star \, m'^\star \, m_1'^\star}{\Pi^0 \, \Pi_1^0 \, \Pi'^0 \, \Pi_1'^0} \\
& W(\Pi^\mu, \Pi_1^\mu \mid \Pi'^\mu, \Pi_1'^\mu) \delta^4(p^\mu + p_1^\mu - p'^\mu - p_1'^\mu) \\
& (f(x,\Pi') f(x,\Pi_1') (1 - f(x,\Pi))(1 - f(x,\Pi_1)) \\
& - f(x,\Pi) f(x,\Pi_1)(1 - f(x,\Pi'))(1 - f(x,\Pi_1'))).
\end{aligned} \tag{20}
$$

This collision integral describes the change in the phase-space distribution function $f(x,\Pi)$ due to the collision of two baryons with effective masses $m^\star$, $m_1^\star$ and momenta Π^μ, Π_1^μ, respectively. The two baryons in the final state of the reaction with masses $m' *$ and $m_1' *$ are labeled by their momenta Π' and Π_1'. The $\delta-$function guarantees energy and momentum conservation in the individual collision while $W(\Pi^\mu, \Pi_1^\mu \mid \Pi'^\mu, \Pi_1'^\mu)$ denotes the transition probability for this reaction which can be expressed in the CMS of the colliding particles by the product of the relative velocity of both colliding particles and the differential cross section for the reaction,

$$W(\Pi^\mu, \Pi_1^\mu \mid \Pi'^\mu, \Pi_1'^\mu) = \left| \frac{\vec{\Pi}}{\Pi^0} + \frac{\vec{\Pi}}{\Pi_1^0} \right| \frac{d\sigma}{d\Omega} \Big|_{\Pi^\mu + \Pi_1^\mu \rightarrow \Pi'^\mu + \Pi_1'^\mu} . \tag{21}$$

For the NN cross section we use the parametrization given by Cugnon [37] and therefore neglect the possible in-medium corrections. However, the corrections due to Pauli-blocking are built in via the factors $1 - f$. We explicitly account for the following baryonic channels:

$$N + N \rightarrow N + N, N + N \rightarrow N + \Delta$$
$$N + \Delta \rightarrow N + N, \Delta + \Delta \rightarrow \Delta + \Delta$$

and propagate the Δ's with the same selfenergies as the nucleons. For the parametrizations of the cross sections of reactions including Δ's see [1].

B. Antiprotons in RBUU

The phase-space distribution function for the antiprotons $f_{\bar{p}}(x, p_{\bar{p}})$ is assumed to follow an equation of motion equivalent to eq. (10), however, with scalar and vector potentials of different strength, i.e.

$$\begin{aligned} U_s^{\bar{p}}(x) &= -g_s^{\bar{p}} \sigma_H(x) \\ U_\mu^{\bar{p}}(x) &= g_v^{\bar{p}} \omega^H(x)_\mu . \end{aligned} \tag{22}$$

Thus the effective mass and the effective momentum of antiprotons are given by

$$m_{\bar{p}}^\star = m + U_s^{\bar{p}}(x) = m - g_s^{\bar{p}} \sigma_H(x) \tag{23}$$

$$\Pi_\mu^{\bar{p}} = p_\mu^{\bar{p}} - U_\mu^{\bar{p}}(x) = p_\mu^{\bar{p}} - g_v^{\bar{p}} \omega^H(x)_\mu . \tag{24}$$

According to the arguments given in section II the coupling constants $g_s^{\bar{p}}$ and $g_s^{\bar{p}}$ are treated as free parameters and will be determined in a comparison of our calculations to experimental data (cf. section VI). Since at subthreshold energies antiprotons can be produced only in a very limited kinematical range we can work here with scalar and vector parts of the

antiproton selfenergies that are not explicitly momentum-dependent. We then obtain the following equation of motion for the antiproton phase-space distribution function

$$\left[\frac{\Pi^{\mu}_{\bar{p}}}{\Pi^{0}{}_{\bar{p}}}\partial^{x}_{\mu} + \left(\Pi^{\nu}_{\bar{p}}F^{\bar{p}}_{\mu\nu} + m^{\star}_{\bar{p}}\left(\partial^{x}_{\mu}m^{\star}_{\bar{p}}\right)\right)\partial^{\mu}_{\Pi_{\bar{p}}}\right] f_{\bar{p}}(x,\Pi_{\bar{p}}) = I^{\bar{p}}_{coll}(x,\Pi_{\bar{p}}) \tag{25}$$

with

$$F^{\mu\nu}_{\bar{p}} = \partial^{\mu}U^{\bar{p}\,\nu}_{v} - -\partial^{\nu}U^{\bar{p}\,\mu}_{v} \tag{26}$$

and the mass-shell constraint

$$\left(\Pi^{2}_{\bar{p}} - m^{\star\,2}_{\bar{p}}\right)\bar{f}\,(x,\Pi_{\bar{p}}) = 0. \tag{27}$$

The collision term $I^{\bar{p}}_{coll}$ (r.h.s. of eq. (25)) includes i) a term $I^{\bar{p}}_{elast}$, describing the elastic antiproton scattering, ii) a term $I^{\bar{p}}_{prod}$, describing the antiproton production, and iii) a term $I^{\bar{p}}_{abs}$ responsible for in-medium $\bar{p}$-absorption. $I^{\bar{p}}_{elast}$ describes elastic baryon-antiproton scattering as well as elastic antiproton-antiproton scattering. While this part of the collision integral $I^{\bar{p}}_{coll}$ can be formulated similarly to the collision term describing bayon-baryon scattering (20) the other terms represent extensions to this integral.

1. Collision term for $\bar{p}$-production

The basis for the description of the antiproton production is the reaction

$$B + B \longrightarrow \bar{p} + p + N + N \equiv 1 + 2 \longrightarrow \bar{p} + 3 + 4 + 5, \tag{28}$$

for which the corresponding covariant collision integral reads

$$\begin{aligned}
&I^{\bar{p}}_{prod}(x,\Pi_{\bar{p}}) = \\
&\frac{4}{(2\pi)^{11}}\int d^3\Pi_1\, d^3\Pi_2\, d^3\Pi_3\, d^3\Pi_4\, d^3\Pi_5 \frac{m^{\star}_1\, m^{\star}_2\, m^{\star}_3\, m^{\star}_4\, m^{\star}_5\, m^{\star}_{\bar{p}}}{\Pi^0_1\,\Pi^0_2\,\Pi^0_3\,\Pi^0_4\,\Pi^0_5\,\Pi^0_{\bar{p}}} \\
&W(\Pi^{\mu}_1,\Pi^{\mu}_2 \mid \Pi^{\mu}_3,\Pi^{\mu}_4,\Pi^{\mu}_5,\Pi^{\mu}_{\bar{p}})\delta^4(p^{\mu}_1 + p^{\mu}_2 - p^{\mu}_3 - p^{\mu}_4 - p^{\mu}_5 - \Pi^{\mu}_{\bar{p}}) \\
&\{f(x,\Pi_1)f(x,\Pi_2)(1-f(x,\Pi_3))(1-f(x,\Pi_4))(1-f(x,\Pi_5))\}\,.
\end{aligned} \tag{29}$$

We have omitted the Pauli-blocking factor for the antiproton in the final state because the number of antiprotons created during a heavy-ion collision in the subthreshold energy regime is negligible. For the same reason we neglect the effects of reaction (28) on the phase-space distribution function of the baryons.

2. Collision term for $\bar{p}$-absorption

In the collision integral $I^{\bar{p}}_{abs}$ we do not treat all possible annihilation reactions separately but sum up all channels in the inclusive annihilation reaction

$$B + \bar{p} \rightarrow X, \tag{30}$$

where X denotes all possible final states (essentially pions) of the baryon-antiproton annihilation. The corresponding energy and momentum conservation reads

$$p^\mu_B + p^\mu_{\bar{p}} = p^\mu_X, \tag{31}$$

where p^μ_B and $p^\mu_{\bar{p}}$ denote the 4-momenta of the baryon and the antiproton, respectively, and p^μ_X stands for the sum of the 4-momenta of all particles in the final state of the annihilation reaction. Reaction (30) then leads to the collision term

$$\begin{aligned} I^{\bar{p}}_{abs}(x, \Pi_{\bar{p}}) = -\frac{4}{(2\pi)^3} \int d^3\Pi_1 d^4\Pi_X \frac{m^\star_1 m^\star_{\bar{p}}}{\Pi^0_1 \Pi^0_{\bar{p}}} \\ W(\Pi^\mu_1, \Pi^\mu_{\bar{p}} \mid \Pi^\mu_X) \delta^4(p^\mu_1 + p^\mu_{\bar{p}} - p^\mu_X) f(x, \Pi_1) f(x, \Pi_{\bar{p}}) \end{aligned} \tag{32}$$

with $W(\Pi^\mu_1, \Pi^\mu_{\bar{p}} \mid \Pi^\mu_X)$ denoting the transition probability for the reaction (30). Integrating (32) over $d^4\Pi_X$ implies in addition to the integration over all final momentum states of a particular reaction a summation over all possible annihilation channels

$$I^{\bar{p}}_{abs}(x, \Pi_{\bar{p}}) = -\frac{4}{(2\pi)^3} \int d^3\Pi_1 \frac{m^\star_1 m^\star_{\bar{p}}}{\Pi^0_1 \Pi^0_{\bar{p}}} W(\Pi^\mu_1, \Pi^\mu_{\bar{p}}) f(x, \Pi_1) f(x, \Pi_{\bar{p}}), \tag{33}$$

where $W(\Pi^\mu_1, \Pi^\mu_{\bar{p}})$ denotes the probability of an antiproton with effective momentum $\Pi^\mu_{\bar{p}}$ annihilating with a baryon with effective momentum Π^μ_1.

IV. ANTIPROTON PRODUCTION IN RBUU

In this section we describe the numerical treatment of antiproton production in our model and present a systematic analysis of the $\bar{p}$-production mechanism in heavy-ion collisions .

A. Numerical implementation

Since the production probability for antiprotons is very small the average time evolution of the nucleus-nucleus collision is not affected and it is justified to treat the $\bar{p}$-production perturbatively [2,31]. In this approach the antiproton invariant differential multiplicity is obtained by summing incoherently over all baryon-baryon collisions and integrating over all residual degrees of freedom. Assuming the antiproton production to take place via reactions of the type

$$B + B \rightarrow \bar{p} + p + N + N \equiv 1 + 2 \rightarrow \bar{p} + 3 + 4 + 5 \tag{34}$$

(B stands for either nucleon or Δ) the invariant multiplicity as a function of the impact parameter can be written as

$$\begin{aligned} E_{\bar{p}} \frac{d^3P(b)}{d^3\Pi_{\bar{p}}} = \sum_{BBcoll} \int d^3\Pi'_3 d^3\Pi'_4 d^3\Pi'_5 \frac{1}{\sigma_{BB}(\sqrt{s})} E'_{\bar{p}} \frac{d^{12}\sigma_{BB\rightarrow\bar{p}+X}\,(\sqrt{s})}{d^3\Pi'_3 d^3\Pi'_4 d^3\Pi'_5 d^3\Pi'_{\bar{p}}} \\ (1 - f(x, \Pi'_3))(1 - f(x, \Pi'_4))(1 - f(x, \Pi'_5)), \end{aligned} \tag{35}$$

where the quantities $\Pi_i\,(i = 1, .., 5)$ denote the in-medium momenta of the participating baryons. $\Pi_{\bar{p}}$ and $E_{\bar{p}}$ stand for the $\bar{p}$ effective momentum and energy while $s = (\Pi_1^\mu + \Pi_2^\mu)^2$ is the squared invariant energy available in the corresponding baryon-baryon collision. An integration over the impact parameter then yields the Lorentz invariant differential production cross section

$$E_{\bar{p}} \frac{d^3\sigma_{\bar{p}}}{d^3\Pi_{\bar{p}}} = 2\pi \int db\, b\ E_{\bar{p}} \frac{d^3P(b)}{d^3\Pi_{\bar{p}}}. \tag{36}$$

We assume the elementary antiproton production cross section $\sigma_{BB\rightarrow\bar{p}+X}(\sqrt{s})$ in all baryon-baryon channels to be equal to $\sigma_{pp\rightarrow\bar{p}+X}(\sqrt{s})$ and employ a parametrization of the free cross section given by [18] (cf. fig. 3; solid line):

$$\sigma_{BB\to\bar{p}+X} = 0.01(\sqrt{s} - \sqrt{s_0})^{1.846}[mb], \tag{37}$$

with $\sqrt{s_0} = 4m_N$ and $m_N = 0.9383\, GeV/c^2$. The dashed and the dotted line in fig. 3 represent extreme alternative parametrizations that will also be used below.

While in free space the threshold for the elementary production reaction is obviously 4 times the nucleon restmass in the medium one additionally has to take into account the selfenergies of all participating particles. The conservation of energy and momentum has to be guaranteed, i.e.

$$p_1^\mu + p_2^\mu = p_3^\mu + p_4^\mu + p_5^\mu + p_{\bar{p}}^\mu, \tag{38}$$

which in terms of effective momenta and selfenergies (cf. eqs. (11) and (24)) yields

$$\begin{aligned} \Pi_1^\mu + U_v^\mu(\mid \vec{p}_1 \mid, x) + \Pi_2^\mu + U_v^\mu(\mid \vec{p}_2 \mid, x) = \Pi_3^\mu + U_v^\mu(\mid \vec{p}_3 \mid, x) + \Pi_4^\mu + \\ U_v^\mu(\mid \vec{p}_4 \mid, x) + \Pi_5^\mu + U_v^\mu(\mid \vec{p}_5 \mid, x) + \Pi_{\bar{p}}^\mu + U_v^{\bar{p}\,\mu}(x). \end{aligned} \tag{39}$$

With the abbreviation

$$\begin{aligned} \Delta^\mu \equiv U_v^\mu(\mid \vec{p}_3 \mid, x) + U_v^\mu(\mid \vec{p}_4 \mid, x) + U_v^\mu(\mid \vec{p}_5 \mid, x) + U_v^{\bar{p}\,\mu}(x) \\ - U_v^\mu(\mid \vec{p}_1 \mid, x) - U_v^\mu(\mid \vec{p}_2 \mid, x) \end{aligned} \tag{40}$$

we obtain in shorthand form

$$\Pi_1^\mu + \Pi_2^\mu = \Pi_3^\mu + \Pi_4^\mu + \Pi_5^\mu + \Pi_{\bar{p}}^\mu + \Delta^\mu. \tag{41}$$

When evaluating the threshold for the reaction in terms of effective momenta, i.e.

$$\vec{\Pi}_{\bar{p}} + \vec{\Pi}_3 + \vec{\Pi}_4 + \vec{\Pi}_5 = \vec{0}, \tag{42}$$

we in general encounter a nonvanishing sum of the vector selfenergies of all participating particles. This leads to the following expression for the threshold

$$\sqrt{s_0} = \sqrt{(m_{\bar{p}}^\star + m_3^\star + m_4^\star + m_5^\star + \Delta^0)^2 - \vec{\Delta}^2}. \tag{43}$$

In the $\sigma - \omega$-model, where the $\bar{p}$-selfenergies result from the corresponding baryon selfenergies by applying charge conjugation, the quantity Δ^μ vanishes and eq. (43) reduces to an expression equivalent to the free threshold with the restmasses replaced by the effective masses of the participating particles.

In order to derive an expression for the differential $\bar{p}$-multiplicity we assume, as in refs. [16–18], that the differential elementary antiproton production cross section is proportional to the phase-space available for the final state:

$$E_3 E_4 E_5 E_{\bar{p}} \frac{d^{12}\sigma_{BB\to NNN+\bar{p}}\,(\sqrt{s})}{d^3\Pi_3 d^3\Pi_4 d^3\Pi_5 d^3\Pi_{\bar{p}}} = \sigma_{BB\to NNN+\bar{p}}(\sqrt{s}) \frac{1}{16\, R_4(\sqrt{s})}$$
$$\delta^4(\Pi_1^\mu + \Pi_2^\mu - \Pi_3^\mu - \Pi_4^\mu - \Pi_5^\mu - \Pi_{\bar{p}}^\mu - \Delta^\mu). \tag{44}$$

Here, the δ-function guarantees the energy and momentum conservation and $\sqrt{s}$ is the invariant energy available for the quasi-particles in the initial state. $R_4(\sqrt{s})$ is the 4-body phase-space integral [38]; it has been included to ensure that the differential cross section is normalized to the total cross section.

B. Sensitivity to the elementary cross section

Now we turn first to the analysis of the antiproton production mechanism itself and consequently neglect all in-medium propagation and absorption effects. For the sake of numerical simplicity we calculate here the $\bar{p}$-production using the baryon-selfenergies obtained from the nonlinear $\sigma - \omega$-model [39] where the $\bar{p}$-selfenergies are determined by charge conjugation from those of the baryons.

Since we are dealing with subthreshold particle production the antiproton cross section will depend strongly on the behaviour of the elementary cross section (37) close to threshold. Since there are no experimental data available for $\sqrt{s} - -\sqrt{s_0} \leq 1$ GeV (cf. fig. 3) we have to rely on an extrapolation of the data to threshold. In order to investigate the dependence of our results on the parametrization of the cross section we display in fig. 4 the invariant differential production probability for the reaction $Si+Si$ at 2.1 GeV/u for different extreme

parametrizations corresponding to the dashed and dotted lines in fig. 3. This uncertainty of up to one order of magnitude has to be kept in mind when drawing any conclusions from the comparision of our work with the experimental data. For our further analysis we will adopt the parametrization (37).

Due to these uncertainties it is justified to neglect the Pauli-blocking effects in the calculation of antiproton production which turn out to reduce the production probability by about 10 to 20% as shown in fig. 5 for the special case of a central $Au + Au$ collision at 2.1 GeV/u. The effects of the Pauli-blocking increase with decreasing beam energy and become less important for lighter systems as e.g. $Ne + Ne$.

C. Probing the high density phase with $\bar{p}$

In order to demonstrate the sensitivity of the antiproton production to the equation of state (EOS) for nuclear matter we display in fig. 6 the invariant differential $\bar{p}$-production probability for the reactions $Au + Au$ and $Si + Si$ at 2.1 GeV/u calculated for different parametrizations of the EOS. The parametersets NL1 and NL3 (cf. ref. [39]) employ the same incompressibility $K = 400$ MeV, but differ in the effective nucleon mass at $\rho = \rho_0$ ($m^\star/m = 0.83$ for NL1; $m^\star/m = 0.7$ for NL3), while NL1 and NL2 employ the same effective mass, but differ in their incompressibility ($K = 200$ MeV for NL2). For both systems we observe a production probability which is enhanced by roughly one order of magnitude for NL3 as compared to that from NL1 and NL2. The reason for this behaviour is obviously the low lying threshold which goes along with the small effective nucleon mass when using the prametrization NL3.

While there is hardly any sensitivity to the incompressibility (NL1 versus NL2) in the light system, one can observe an increase of the production probability by a factor of 3 with decreasing incompressibility in the heavy system. The reason for this sensitivity is given in fig. 7 where we show the differential $\bar{p}$-multiplicity $dN/d\rho$ as a function of the baryon density ρ/ρ_0 at the individual antiproton production point for $Si + Si$ (dashed line; multiplied by

a factor of 50) and $Au + Au$ at 2.1 GeV/u. It is clearly seen that almost all antiprotons are produced at $\rho \geq 3\rho_0$ in the heavy system while the majority of antiprotons is created between $2\rho_0$ and $3\rho_0$ in the light system. This difference is easily understood in terms of the pile-up of density in the heavy system. In the case of $Au + Au$ reactions high densities are obtained for parametersets that describe a rather soft EOS [40]. Thus compared to NL1 the parameterset NL2 leads to a larger density in the reaction zone resulting also in a higher antiproton production cross section.

D. Variation with the impact parameter

Since central collisions lead only to minor contibutions to the inclusive cross section in heavy-ion collisions it is of interest to study the $\bar{p}$-multiplicity as a function of the impact parameter b. For this purpose we show in fig. 8 the calculated differential antiproton multiplicity for $Si + Si$ at 2.1 GeV/u multiplied by $2\pi b$ as a function of b (solid line). This quantity can be approximately fitted by (dotted line)

$$\frac{d\sigma(b)}{db} = 2\pi b P(b=0)\ S(b), \tag{45}$$

where S(b) represents the geometrical overlap of two nuclei with mass number A_1 and A_2 as a function of the impact parameter. Assuming $A_1 > A_2$ the overlap function S(b) reads

$$\begin{aligned} S(b) = \frac{1}{\pi R_2^2} \Bigg\{ & R_1 \arccos\left[\frac{b^2 + R_1^2 - R_2^2}{2R_1 b}\right] + R_2 \arccos\left[\frac{b^2 + R_2^2 - R_1^2}{2R_2 b}\right] \\ & - \frac{1}{4b^2}\left[(b^2 + R_1^2 - R_2^2) + (b^2 + R_2^2 - R_1^2)\right]\sqrt{2(R_1^2 + R_2^2)\, b^2 - b^4 - (R_1^2 - R_2^2)^2} \Bigg\} \\ & \text{for } R_2 \leq b \leq R_1 \end{aligned}$$

and

$$S(b) = 1$$

$$\text{for } b < R_2 < R_1 \tag{46}$$

with $R_1 = aA_1^{\frac{1}{3}}$ and $R_2 = aA_2^{\frac{1}{3}}$. In case of symmetric systems this reduces to

$$S(b) = \frac{1}{\pi R^2} \left\{ 2R \arccos \frac{b^2}{2Rb} - b \left(R^2 - \frac{b^4}{4} \right)^{\frac{1}{2}} \right\}. \qquad (47)$$

A more systematic analysis with respect to A_1 and A_2 shows that an optimal fit to the impact parameter dependence is obtained for the radius parameter $a = 1.1 fm$.

E. Baryonic decomposition

It is well known from transport calculations [18,40] that heavy mesons and antiprotons are dominantly produced via multiple baryon-baryon collisions where especially nucleon-resonance channels play an important role. To gain further insight in the mechanism of $\bar{p}$-production we analyse the relative contribution from various channels in more detail by counting the number of collisions N_1+N_2 that two baryons have undergone before producing an antiproton in a mutual collision and determine the corresponding production probability as a function of $N_1 + N_2$ for the channels NN, $N\Delta$ and $\Delta\Delta$ separately. The resulting distributions are displayed in fig. 9 for the reactions $Si + Si$, $Ca + Ca$ and $Au + Au$ at 2.0 and 2.5 GeV/u. The full histograms denote the channel $NN \rightarrow \bar{p} + X$, the open histograms denote the channel $N\Delta \rightarrow \bar{p}+X$ and the hatched histograms the $\Delta\Delta \rightarrow \bar{p}+X$, respectively. Table I shows the relative contributions integrated over N_1+N_2. From table 1 we can extract a general trend: The NN-channel is obviously of minor importance. In heavier systems the contributions from resonances to the $\bar{p}$-production are generally higher as compared to lighter systems. This correlates with the higher density pile-up in heavy systems. The resonances become, furthermore, more important with decreasing beam energy.

In order to study this phenomenon in more detail we display in fig. 10 the relative contributions to the $\bar{p}$-yield for $Ca+Ca$ as a function of the beam energy. The contribution from the NN-channel is below the 10% level for $E_{beam} \leq 2.5 GeV/u$. While for higher energies the ΔN-channel dominates the production of antiprotons the $\Delta\Delta$- and the ΔN-channel are approximately equally important in the energy regime between 2.4 GeV/u and 2.0 GeV/u. Below 2.0 GeV/u the $\Delta\Delta$-channel is clearly the dominant one.

From the analysis of this section we can conclude that, as far as antiproton production is concerned, the nucleon-resonances act as energy reservoirs that can release their energy in baryon-baryon collisions to allow for $\bar{p}$-production. That the resonances are populated in sufficiently large numbers is a consequence of the formation of resonance matter [43] in relativistic heavy-ion collisions.

F. Sensitivity to in-medium $\bar{p}$-properties

The threshold for the elementary $\bar{p}$-production reaction according to (43) depends on the in-medium properties of the antiprotons . In order to investigate this dependence we calculate the $\bar{p}$-production probability for $Ni + Ni$ at 1.85 GeV/u (central collision) for a variety of different antiproton selfenergies : In the calculation shown in the upper part of fig. 11 the $\bar{p}$-production probability was determined using a fixed vector part of the antiproton selfenergy ($U_0^{\bar{p}} = -98$ MeV at $\rho = \rho_0$) while varying the scalar part $U_s^{\bar{p}}$ (see figure caption). The results displayed in the bottom part of fig. 11 were obtained by varying the vector part while keeping the scalar part $U_s^{\bar{p}}$ fixed at -159 MeV at $\rho = \rho_0$. The same analysis performed for other systems than $Ni + Ni$ lead to quite similar results. Thus we conclude that the antiproton production cross section exhibits an extreme sensitivity to the in-medium $\bar{p}$-properties. This sensitivity will be used below to obtain approximate values for the $\bar{p}$ selfenergy in comparison to experimental data.

V. IN-MEDIUM $\bar{P}$ PROPAGATION AND ABSORPTION

The antiprotons produced in individual baryon-baryon collisions can be annihilated while propagating out of the dense nuclear medium. Since we expect the $\bar{p}$-annhilation to dominate the antiproton spectra a proper treatment of this reaction channel is crucial for a comparison with experimental data. In order to be able to treat the $\bar{p}$-absorption and propagation sufficiently well we employ a new numerical method which allows to calculate the propagation as well as the antiproton absorption nonperturbatively. We neglect the elastic scattering

of antiprotons with the surrounding baryons; according to ref. [25] this elastic scattering only causes a flattening of the antiproton momentum spectra. The numerical details of our method are presented in Appendix A. In this section we concentrate on the effects of in-medium absorption and propagation of the antiprotons .

During a heavy-ion collision or a proton-nucleus reaction the antiprotons are created with effective masses $m^\star_{\bar{p}}$ and momenta $\Pi^\mu_{\bar{p}}$. These particle properties change according to the surrounding medium as the antiprotons leave the reaction zone. At the end one observes free antiprotons with kanonical momenta $p^\mu_{\bar{p}}$. Since the properties of the antiprotons are determined by their optical potential one expects significant effects of the $\bar{p}$-propagation on the $\bar{p}$-spectra. We analyse these effects in figs. 12 and 13. Fig. 12 shows the variations in the $\bar{p}$-spectra due to different antiproton selfenergies for a central $Si + Si$ collision at 2.1 GeV/u at $\Theta_{lab} = 0^o$. The production probability is identical for all cases. The calculations shown in the top part of this figure were performed for $U^{\bar{p}}_s = 0$ and different vector parts (see fig. 12). The bottom part of this figure shows the result of calculations for $U^{\bar{p}}_\mu = 0$ and varying scalar parts of the antiproton selfenergy . Comparing both figures we conclude, as for the $\bar{p}$-production itself, that the effects of the scalar and vector part of the selfenergy on the $\bar{p}$-spectra are qualitatively and quantitatively similar. Attractive potentials result in a reduction of the $\bar{p}$-momenta as the antiprotons leave the reaction zone while repulsive potentials lead to enhanced $\bar{p}$-momenta.

Fig. 13 displays the same analysis for $p + Cu$ at 4.0 GeV at $\Theta_{lab} = 0^o$. Again, the production was calculated identically for all three cases. Comparing the $\bar{p}$-spectrum obtained for free propagation ($U_{sep} = 0$) with the one obtained using a weakly attractive optical potential ($U_{sep} = -90$ MeV) one observes a slight shift of the spectrum towards lower momenta. This shift is easily explained by the loss of kinetic energy that occurs as the effective mass $m^\star_{\bar{p}}$ increases to the value of the restmass when the antiprotons leave the reaction zone. Using a strongly attractive optical potential ($U_{sep} = -560$ MeV) one realizes in addition to this shift a reduction of the spectrum due to the propagation effects. Contrary to heavy-ion collisions the target-nuclei in proton-nucleus collisions are not destroyed during

those timescales when the antiprotons move into the continuum. This means that the target nuclei build a potential barrier which the antiprotons have to overcome when leaving the nuclei. The low energy antiprotons cannot overcome this potential wall and get trapped in the nucleus which leads to the observed reduction in the $\bar{p}$-spectrum.

Figs. 12 and 13 clearly show that the antiproton in-medium propagation has an impact on the differential $\bar{p}$-spectra. Therefore it is important to apply the complete mean-field dynamics of the RBUU model when describing the propagation of antiprotons .

Now we turn to the in-medium antiproton absorption ($\bar{p}+B \to X$). Due to the fact that there is no information available on the in-medium cross section we have to rely on the free cross section in the parametrization from [13](6). In our transport calculation we replace the free $s-s_0$ with that determined from the in-medium properties of the colliding particles, i.e. $s = (\Pi^0_{\bar{p}} + \Pi^0_B)^2 - (\vec{\Pi}_{\bar{p}} + \vec{\Pi}_B)^2$ is the squared invariant energy available in the elementary antiproton-baryon collision while $s_0 = (m^\star_{\bar{p}} + m^\star_B)^2$ denotes the squared sum of the effective masses of the colliding particles. The dashed line in fig. 1 represents a cutoff at 100 mb which is introduced to simulate possible in-medium screening effects. The value of 100 mb for the cutoff is in line with the annihilation radius for proton-antiproton annihilation derived in a optical model calculation [41]. Fig. 14 shows the number of antiproton-baryon collisions as a function of the corresponding value of σ_{abs} for a central reaction $Si + Si$ at 2.1 GeV/u. Since only a small fraction of all events lies in the region of $100 - 192$ mb our results do not depend significantly on the cutoff. Similar studies for proton-nucleus collisions show even less sensitivity to this cutoff since the antiprotons move with higher momenta with respect to the target nucleus.

In order to study the $\bar{p}$-absorption effects on the antiproton spectra from heavy-ion collisions we have performed calculations using different fixed absorption cross sections in comparison to the dynamically determined cross section (6). Fig. 15 shows a full calculation for the system $Si + Si$ at 2.1 GeV/u at $\Theta_{CM} = 0^o$. The top line denotes the calculated $\bar{p}$-probability without absorption using the baryon selfenergies obtained from the nonlinear $\sigma - \omega-$model with $\bar{p}$-selfenergies obtained via charge conjugation from the baryon selfener-

gies. The lower lines represent calculations with different constant absorption cross sections while the solid line results from a calculation using the parametrization (6). This figure clearly reflects the dominant role of the in-medium absorption of antiprotons which leads to a reduction in $\bar{p}$-probability by approximately two orders of magnitude; these absorption rates agree with those determined by Li et al. [25]. Furthermore, the spectral distribution obtained when using the parametrization (6) is - except for small deviations at low antiproton momenta - almost identical to the distribution obtained for a constant cross section of 70 mb. This value corresponds approximately to the mean value of the distribution displayed in fig. 14.

In this context we note that in proton-nucleus reactions the corresponding mean value of the elementary $\bar{p}$-absortion cross section is aproximately 50 mb which leads to absorption factors of $10-30$ depending on the size of the target nucleus and the beam energy. The difference in antiproton absorption between heavy-ion collisions and proton-nucleus reactions is mainly due to the different kinematics in both cases: During a heavy-ion collision most of the antiprotons are created in the CMS of the collision which implies that the relative velocity of the antiprotons and the surrounding baryonic medium is low. This leads to a small $s-s_0$ for the annihilation reaction and results in high values of the absorption cross section (see fig. 1). In contrast to this situation the antiprotons produced in proton-nucleus collisions move with momenta of around 1 GeV/c through the baryonic medium which leads to smaller annihilation rates. Another difference in both types of reactions is that the $\bar{p}$-absorption in proton-nucleus collisions takes place at a maximum density ρ_0 while the antiprotons produced in heavy-ion collisions experience higher densities (cf. fig. 7) which again leads to an increase in the absorption probability.

Finally we study the impact parameter dependence of the antiproton absorption. For this purpose we have to investigate a physical quantity that does not show the impact parameter dependence of the antiproton production mechanism. The ratio R of the differential $\bar{p}$-probability calculated including absorption and the differential production probability meets this requirement. In Fig. 16 we display R for $Ni+Ni$ at 1.85 GeV/u, $Ne+Ni$ at 2.0 GeV/u

and $Si+Si$ at 2.1 GeV/u as a function of b/b_{max} where b denotes the impact parameter and b_{max} is the sum of the corresponding radii of target and projectile. The ratio R is evaluated for zero antiproton momentum in the CMS of the corresponding heavy-ion collision . The dots represent the values of R calculated in the RBUU model and the solid lines correspond to fits to these numerical data using the function

$$R\,(b/b_{max}) = A - (1 + e^{\frac{(b/b_{max}-B)}{C}})^{-1}. \tag{48}$$

The parameters A, B and C are given in table II. Except for peripheral collisions ($b/b_{max} > 0.6$) the ratio R is determined by the constant A for all systems. This means that the $\bar{p}$-production spectra for $b/b_{max} \leq 0.6$ are reduced due to the absorption mechanism by a constant factor determined by the size of the system. The parameters B and C are similar for all systems considered. This leads to the conclusion that the absorption mechanism is similar for all systems and can be understood by means of simple geometrical considerations.

VI. COMPARISON WITH EXPERIMENTAL DATA

After the systematical analysis of the in-medium antiproton production and absorption mechanism we now turn to the comparison of our calculations with the most recent data from KEK and GSI. In order to perform this comparison we describe the $\bar{p}$-selfenergies on the basis of the $\sigma-\omega-$model with free coupling parameters $g_s^{\bar{p}}$ and $g_v^{\bar{p}}$. The comparison with the experimental data will allow to approximately determine these parameters and then provide first information on the antiproton potential in the dense medium. The quasi-particle properties, i.e. the nucleon selfenergies $U_s(x,p), U_\mu(x,p)$, of the baryons participating in the $\bar{p}$-production reaction are taken from refs. [33–35]. $U_s(x,\,p)$ and $U_\mu(x,\,p)$ are fixed to reproduce the saturation properties of nuclear matter, the empirical proton-nucleus optical potential as well as the density dependence of U_s and U_μ from Dirac-Brueckner theory [36]. For orientation the actual values for $U_s(p)$ and the zero'th component of the vector field $U_0(p)$ are displayed in fig. 17 for $\rho_0(\approx 0.17 fm^{-3}), 2\rho_0$, and $3\rho_0$.

Before we present the results of the calculations using these expressions for the baryon selfenergies we give a brief description of the numerical method used to implement these selfenergies into the antiproton production process. Since we deal with explicit momentum dependent selfenergies ($U_s(x,\, p)$, $U_\mu(x,\, p)$) for the baryons their effective momenta and masses are given by

$$\Pi_j^\mu = p_j^\mu - U_v^\mu(\mid \vec{p}_j \mid, x) \tag{49}$$

$$m_j^\star = m + U_s(\mid \vec{p}_j \mid, x) \tag{50}$$

$$j = 1,\, \cdots,\, 5,$$

while the corresponding quantities for the antiprotons read

$$\Pi_{\bar{p}}^\mu = p_{\bar{p}}^\mu - U_v^{\bar{p}\,\mu}(x) \tag{51}$$

$$m_{\bar{p}}^\star = m + U_s^{\bar{p}}(x). \tag{52}$$

The elementary $\bar{p}$-production events occuring at location $\vec{x}$ are evaluated in the corresponding local rest frame (LRF) of the nuclear matter ($j_\mu = (\rho, 0, 0, 0)$). In this frame the spatial components of the vector selfenergies vanish by definition. This implies that the vector components of the effective and the canonical momenta of all particles are the same (49, 51). The spatial components of the quantity Δ^μ defined in eq. (40) also vanish. Energy and momentum conservation then yields

$$\Pi_1^0 + \Pi_2^0 = \Pi_3^0 + \Pi_4^0 + \Pi_5^0 + \Pi_{\bar{p}}^0 + \Delta^0, \tag{53}$$

$$\vec{p}_1 + \vec{p}_2 = \vec{p}_3 + \vec{p}_4 + \vec{p}_5 + \vec{p}_{\bar{p}}. \tag{54}$$

In order to calculate the $\bar{p}$-production probability we first have to evaluate the threshold $\sqrt{s_0}$ in the LRF. In the CMS of the particles in the final state the threshold is obtained for the kinematical situation with all particles at rest. Thus in the LRF these particles move at threshold with identical velocities. The momenta of the baryons and the antiproton do not necessarily have to be equal because the effective masses of the nucleons and the

antiproton can differ from each other. In order to guarantee momentum conservation we use the following ansatz for the effective masses of the baryons and the antiprotons

$$\mid \vec{p}_j \mid \; = \frac{m^\star(\mid \vec{p}_j \mid)}{3m^\star(\mid \vec{p}_j \mid) + m^\star_{\bar{p}}} \mid \vec{p}_1 + \vec{p}_2 \mid, \tag{55}$$

$$\mid \vec{p}_{\bar{p}} \mid \; = \frac{m^\star_{\bar{p}}}{3m^\star(\mid \vec{p}_j \mid) + m^\star_{\bar{p}}} \mid \vec{p}_1 + \vec{p}_2 \mid . \tag{56}$$

Since each baryon mass depends itself on the momentum of the corresponding baryon these equations are iterative equations for the absolute value of the momenta. Using these effective masses the threshold for antiproton production in the LRF reads

$$\sqrt{s_0} = \sqrt{(3\Pi^0_j + \Pi^0_{\bar{p}} + \Delta^0)^2 - (3\vec{\Pi}_j + \vec{\Pi}_{\bar{p}})^2}. \tag{57}$$

$\bar{p}$-production takes place if the invariant energy $\sqrt{s}$ ($s = (\Pi^0_1 + \Pi^0_2)^2 - (\vec{\Pi}^2_1 + \vec{\Pi}^0_2)^2$) of the baryons in the initial channel lies above the threshold $\sqrt{s_0}$. According to definition (44) the elementary antiproton production cross section is a function of the invariant energy $\sqrt{s'}$ available for the particles in the final state of the production reaction

$$\sqrt{s'} = \sqrt{(\Pi^0_3 + \Pi^0_4 + \Pi^0_5 + \Pi^0_{\bar{p}})^2 - (\vec{p}_3 + \vec{p}_4 + \vec{p}_5 + \vec{p}_{\bar{p}})^2} \tag{58}$$

Using (53) and (54) this reads

$$\sqrt{s'} = \sqrt{(\Pi^0_1 + \Pi^0_2 - \Delta^0)^2 - (\vec{p}_1 + \vec{p}_2)^2}. \tag{59}$$

This equation shows that in order to calculate the production probability one has to know the momenta of the particles in the final state of the elementary production reaction when employing momentum dependent potentials $U_s(x, p)$ and $U_\mu(x, p)$ for the baryons.

Since we are dealing with subthreshold particle production the main contribution to the production cross section will arise from events with collinear baryon momenta because this kinematical situation minimizes the kinetic energy of the baryons. Based on this argument we assume for the momenta of the baryons in the final state

$$\vec{p}_j = \frac{1}{3}(\vec{p}_1 + \vec{p}_2 - \vec{p}_{\bar{p}}). \tag{60}$$

We have applied the above mentioned formalism to evaluate the antiproton cross section for the reactions $p +^{12} C$ and $p+^{63}$Cu at bombarding energies of 5, 4, and 3.5 GeV. The corresponding invariant cross sections in comparison with the data of ref. [11] are shown in fig. 18 as a function of the momentum of the emitted antiproton in the lab. frame at $\Theta = 0^o$, assuming free antiprotons, i.e. $g_s^{\bar{p}}, g_v^{\bar{p}} = 0$. The calculations slightly underestimate the experimental data, but already approximately reproduce the shape of the momentum-spectra as well as the dependence on bombarding energy and mass. The $\bar{p}$ reabsorption amounts to a factor of 12 in case of ^{12}C and to a factor of 19 for ^{63}Cu roughly in line with simple geometrical estimates.

When adjusting the constant $g_s^{\bar{p}}$ such that the scalar potential (18) becomes slightly attractive (-50 to -100 MeV at ρ_0) the reproduction of the data improves at all energies significantly which is exemplified for 4.0 GeV by the dashed line in fig. 18. In the above comparison we cannot distinguish between scalar and vector antiproton selfenergies because both yield similar results for the $\bar{p}$ spectrum if the same Schrödinger-equivalent optical potential is achieved. Furthermore, when using antiproton selfenergies in line with the relativistic mean-field theories [30], i.e. changing only the sign of the nucleon vector potential, we overestimate the $\bar{p}$ yield by more than an order of magnitude at all energies for both systems.

We now turn to the nucleus-nucleus case. The calculated antiproton invariant differential cross section for the reaction $^{28}Si +^{28} Si$ at 2.1 GeV/A and Ni + Ni at 1.85 GeV/u is shown in fig. 19 in comparison to the experimental data of ref. [9] and ref. [12]; the upper lines represent the results of the calculations for free antiprotons without including any reabsorption. When taking care of antiproton annihilation according to eq. (A2) the yields drop to the lower full lines. In the case of $Ni+Ni$ the data are now underestimated sizeably. However, using attractive scalar (or vector) selfenergies at $\rho = \rho_0$ of about -100 to -150 MeV we reproduce the data for $Ni + Ni$, for $Si + Si$, however, we miss the data point at $p = 1$ GeV/c.

We thus use a potential of -100 MeV at $\rho = \rho_0$ to predict the differential $\bar{p}$-excitation

function in $Ni+Ni$ collisions from 1.4 to 2.5 GeV/u (fig. 20), a system that will be explored at GSI in the near future [42].

The different value for the attractive antiproton field at $\rho = \rho_0$ in $p + A$ and $A + A$ reactions is due to the fact that in $p+A$ collisions the antiprotons move with momenta of 1 - 2 GeV/c with respect to the nuclear medium, whereas in $A + A$ collisions the antiprotons have smaller momenta in the nucleus-nucleus center-of-mass frame. In view of uncertainties of our present studies with respect to the elementary production cross sections close to the thresholds we provide areas for the antiproton Schrödinger equivalent potential at $\rho = \rho_0$ in fig. 21, as extracted from the comparison with the experimental data for $p + A$ and $A + A$ reactions. These areas are far from the values expected by charge conjugation from the familiar $\sigma - \omega$ model [30] (dashed line) and thus exclude relativistic mean-field models with the same parameter-sets for nucleons and antinucleons. However, our extracted values are well in line with a Schrödinger-equivalent potential (solid line in fig. 21) as calculated from the dispersion relation (see equations (1) - (5)). Crucial for this result is the correct momentum dependence for the $p + A$ potential in the entrance channel. If we use the original Walecka model without the momentum dependent coupling strength we are forced to compensate for the strong repulsion with much deeper antiproton potentials.

The primordial antiproton production rates and the reduction due to absorption obtained here agree well with those obtained by Li et al. [25]. These authors also get agreement with the data for $Si + Si$, however, by using the very deep $\bar{p}$-potential obtained by charge conjugation from the Walecka model and the corresponding strong repulsion in the entrance channel; using the same model we also reproduce the data, as well as their calculations within a factor of two. However, the entrance channel potential is much too repulsive, as mentioned in section 3.1, so that an unphysically deep antiproton potential is needed to compensate for this repulsion. This fact shows that the conclusion of ref. [25] that the agreement of their calculation with the data supports the assumption of a very deep G-parity transformed nucleon potential for the antiprotons is not justified.

VII. SUMMARY

In this work we have evaluated the differential cross section for $\bar{p}$ production for proton-nucleus and nucleus-nucleus reactions in the subtreshold regime by considering on-shell baryon-baryon production channels involving nucleons and Δ's with their in-medium quasi-particle properties and treating $\bar{p}$ propagation and annihilation nonperturbatively. The quasi-particle properties of the nucleons are fixed in our approach by the nuclear saturation properties, the proton-nucleus empirical potential as well as Dirac-Brueckner calculations at higher density. By varying especially the antiproton selfenergy we have shown that the differential $\bar{p}$ spectra are highly sensitive to the antiproton quasi-particle properties. Though we still have to rely on proper extrapolations to threshold of the elementary process $p + p \rightarrow \bar{p} + X$, the latter sensitivity can be used to obtain approximate values for the $\bar{p}$ Schrödinger-equivalent potential from a systematic comparison to the available experimental data.

In this respect we have performed a systematic study of p-nucleus and nucleus-nucleus collisions in a broad kinematical regime and compared our numerical results to the data from KEK [11] and GSI [12]. We find a consistent description of all data employing a rather weak attractive potential for the antiprotons which is well in line with a dispersive potential extracted from the dominant imaginary part of the antiproton selfenergy due to annihilation. Essential for this result is the use of the correct momentum dependence of the nucleon-nucleus potential in the entrance channel. Although the validity of the simple dispersive model used here may be questionable at higher densities and the extrapolation of the elementary $\bar{p}$-production cross section down to threshold introduces an uncertainty, the consistency of the $\bar{p}$-potentials obtained from a fit to the data with those calculated in the dispersive model indicates that the basic antiproton production mechanism in $p+A$ and $A+A$ reactions is understood.

It has become clear that the baryonic production channels at subthreshold energies involve dominantly one or two nucleon resonances and that the production proceeds at the

highest densities that can be reached in a nucleus-nucleus reaction. Only at these high densities the relative population of nucleon resonances (≈ 30 % as shown in [43]) as well as the nucleon-resonance collision rate are high enough to allow for $\bar{p}$ production. Otherwise the resonances decay to a nucleon and a pion before colliding with another baryon such that the energy stored in the resonance gets lost for the production.

We note in closing that the antiproton production studies at the AGS [44–46] around 15 GeV/u, although far above the free production threshold, might yield further information on the dynamics and selfenergies of antiprotons at even higher densities.

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APPENDIX A: THE WEIGHTED TESTPARTICLE METHOD

In the following we present the weighted testparticle method used to implement the antiproton production, absorption and propagation in the RBUU model. It is especially suited for the simulation of processes with low production probabilities and/or high in-medium absorption cross sections for which conventional testparticle methods fail because of low statistics.

Assuming that during a calculation N elementary baryon-baryon collisions with sufficient energy for antiproton production occur, we define for each collison i ($i\epsilon\{1, \cdots, ,N\}$) a three-dimensional momentum grid in the reference frame (CMS of the heavy-ion collision or lab-system). In order to calculate the production probability for each collision i we transform this grid into the system that fullfills eq. (42) or into the LRF (see eqn. (49) to (60)). After calculating the invariant differential $\bar{p}$-production probability $w^{(i)}_{klm}$ for each grid point $\vec{p} = (k\Delta p_x,\, l\Delta p_y,\, m\Delta p_z)$ the momentum grid is transformed back into the reference frame. To obtain the total invariant differential production probability without absorption for a heavy-ion collision or a proton-nucleus reaction one has to sum up the contributions from all the N elementary production reactions

$$W_{klm} = \sum_{i=1}^{N} w^{(i)}_{klm}. \tag{A1}$$

In order to calculate the antiproton probability including propagation through the dense medium and absoption we start out with the momentum grid described above. For all N baryon-baryon collisions contributing to the antiproton production we place a testparticle representing an antiproton on every point of the momentum grid. This yields additional j ($j = k \cdot l \cdot m$) testparticles for each of the N baryon-baryon collison events. The effective masses and momenta of these testparticles are determined according to both the location on the momentum grid and the spatial coordinate where the baryon-baryon collision takes place. In addition we attach variable weights to the testparticles. The weight $w'^{(i)}_h$ of the h-th testparticles 'created' in the i-th collision denotes the invariant differential production

probability $w_{klm}^{(i)}$ at the corresponding grid point. The result of this procedure is an ensemble of testparticles representing the produced antiprotons that contain information about the differential $\bar{p}$-distribution for each relevant baryon-baryon collision. The entire testparticle distribution together with the corresponding weights represents the phase-space distribution of the antiprotons produced in a heavy-ion collision or a proton-nucleus reaction.

We now describe how we treat this ensemble of testparticles in order to calculate the antiproton propagation and absorption: Each testparticle is propagated by means of the equation of motion for the antiparticle phase-space distribution function (25). At the end of each timestep the absorption rate for the testparticles is calculated according to their weights. In order to perform this task we convert the collision integral (33) into a differential equation for the testparticle weights

$$\begin{aligned} \frac{dw_h^{\prime(i)}}{dt} \mid_{x,\Pi_{\bar{p}}} &= -\frac{4}{(2\pi)^3} \int\int \frac{d^3\Pi_B}{\Pi_B^0} d^4\Pi_X m_B^\star W(\bar{p}+B \rightarrow X) \\ & \delta^4(\Pi_{\bar{p}}^\mu + \Pi_B^\mu - \Pi_X^\mu) f(x^\mu, \Pi_B^\mu) w_h^{\prime(i)} \mid_{x,\Pi_{\bar{p}}}, \end{aligned} \tag{A2}$$

where x^μ is the space-time coordinate where the annihilation takes place. $\Pi_{\bar{p}}$, Π_B, $m_{\bar{p}}^\star$ and $m_B^\star$ denote the effective momenta and masses of the antiprotons and the baryons, respectively. This differential equation leads to the following changes in the testparticle weights in timesteps Δt,

$$\begin{aligned} w'(t_{j+1})_h^{(i)} &= w'(t_j + \Delta t)_h^{(i)} \\ &= w'(t_j)_h^{(i)}\, exp(-\int_{t_j}^{t_{j+1}} \int \frac{d^3\Pi_B}{\Pi_B^0} m_B^\star W(\bar{p}+B \rightarrow X) f(x^\mu, \Pi_B^\mu) dt). \end{aligned} \tag{A3}$$

Solving the integral in the exponent of (A3) by means of the local density approximation (LDA) [47] leads to

$$w'(t_{j+1})_h^{(i)} = w'(t_j)_h^{(i)} exp(-\frac{1}{\Delta V N_t} \sum_{j \varepsilon V_i} \mid \frac{\vec{\Pi}_{\bar{p}}}{\Pi_{\bar{p}}^0} - \frac{\vec{\Pi}_{B_j}}{\Pi_{B_j}^0} \mid \sigma(\bar{p} + B_j \rightarrow X)\Delta t), \tag{A4}$$

with N_t being the number of testparticles per nucleon used to model the baryon phase-space distribution and ΔV being the normalization volume used in the RBUU model to evaluate

densities and currents. Eq. (A4) allows for a nonperturbative evaluation of high absorption rates without a reduction of the number of testparticles.

At the end of the simulation we project the weight of each antiproton testparticle obtained in the final timestep t_f of our calculation on the three-dimensional momentum grid (see above)

$$\tilde{w}'^{(i)}_h(t_f,\, p_x,\, p_y,\, p_z) \rightarrow \tilde{w}'^{(i)}_{klm} \tag{A5}$$

and sum up all contributions in order to obtain the invariant differential antiproton probability for the corresponding heavy-ion collision or proton-nucleus reaction .

APPENDIX B: FIGURE CAPTIONS

fig.1: Free annihilation cross section for $\bar{p} + p \rightarrow X$. Dots: experimental data from [28]; solid line: parametrization (6).

fig.2: Real part of the antiproton selfenergy as a function of its kinetic energy using different parameters B in (6) for the annihilation cross section.

fig.3: Inclusive antiproton cross section in a pp collision. The solid line indicates the parametrization (37). The dashed and dotted lines show 'extreme' alternative extrapolations to the threshold. The experimental data are taken from [16].

fig.4: Invariant differential production probability for $Si + Si$ at 2.1 GeV/u in the CMS ($\Theta = 0^o$; b = 0; EOS: K = 200 MeV, $m^\star/m = 0.7$ at $\rho = \rho_0$) using different parametrizations for the elementary production cross section according to fig. 3.

fig.5: Effects of Pauli-blocking for $Au + Au$ at 2.1 GeV/u in the CMS ($\Theta = 0^o$, $b = 0$); Solid line: Pauli-blocking included; dashed line: no Pauli-blocking.

fig.6: Differential $\bar{p}$-production probability for $Si + Si$ (top) and$Au + Au$ (bottom) at 2.1 GeV/u in the CMS ($\Theta = 0^o$, $b = 0$) using different parametrizations for the EOS; NL1: K = 400 MeV, $m^\star/m = 0.83$; NL2: K = 200 MeV, $m^\star/m = 0.83$; NL3: K = 200 MeV, $m^\star/m = 0.83$ at $\rho = \rho_0$.

fig.7: Production probability as a function of ρ/ρ_0 for $Au + Au$ (solid line) and $Si + Si$ (dashed line; enhanced by a factor of 50) for 2.1 GeV/u; $\Theta_{CM} = 0^o$, b = 0.

fig.8: $\bar{p}$-multiplicity for $Si + Si$ at 2.1 GeV/u as a function of the impact parameter b weighted with $2\pi b$; calculation: solid line; analytic formula: dashed line (cf. text).

fig.9: Contributions to the production from different channels: NN (filed histograms), $N\Delta$ (open histograms) and $\Delta\Delta$ (hatched histograms) for $Si + Si$, $Ca + Ca$ and

$Au + Au$ at 2.0 GeV/u and 2.5 GeV/u.

fig.10: Relative contributions to the $\bar{p}$-production from different channels as a function of the beam energy for $Ca + Ca$; NN (dotted line), $N\Delta$ (solid line) and $\Delta\Delta$ (dashed line).

fig.11: Differential $\bar{p}$-production probability for a central $Ni + Ni$ collision at 1.85 GeV/u ($\Theta_{CMS} = 0^o$) as a function of the antiproton momentum.
Top: fixed $U_0^{\bar{p}} = -98$ MeV at $\rho = \rho_0$ and variing $U_s^{\bar{p}}$ at $\rho = \rho_0$: -159 MeV (solid), -100 MeV (dashed), -40 MeV (dotted) and 0 (dashed-dotted).
Bottom: fixed $U_s^{\bar{p}} = -159$ MeV at $\rho = \rho_0$ and variing $U_0^{\bar{p}}$ at $\rho = \rho_0$: -98 MeV (solid), -72 MeV (dashed), 0 (dotted) and $+72$ MeV (dashed-dotted).

fig.12: Effects of the in-medium propagation on the $\bar{p}$-sprectrum of $Si + Si$ at 2.1 GeV/u under 0^o in the CMS.
Top: $U_s^{\bar{p}} = 0$ and $U_0^{\bar{p}} = -72$ MeV (dashed), 0 (solid) and $+72$ MeV (dotted) at $\rho = \rho_0$.
Bottom: $U_0^{\bar{p}} = 0$ and $U_s^{\bar{p}} = -100$ MeV (dashed), 0 (solid) and $+100$ MeV (dotted) at $\rho = \rho_0$.

fig.13: Effects of the in-medium propagation on the $\bar{p}$-spectrum for the reaction $p+Cu$ at 4.0 GeV, b= 0, $\Theta_{lab} = 0^o$ for different optical potentials: $U_{sep} = 0$ (dotted), $U_{sep} = -90$ MeV (solid) and $U_{sep} = -560$ MeV (dashed).

fig.14: Number of antiproton -baryon collisions for a central $Si + Si$ reaction at 2.1 GeV/u as a function of the corresponding elementary $\bar{p}$-annihilation cross section.

fig.15: Antiproton spectra for the reaction $Si + Si$ at 2.1 GeV/u (b = 0, $\Theta_{CMS} = 0^o$) using different elementary annihilation cross sections: upper line: no absorption; dotted line: $\sigma_{abs} = 60$ mb; dashed-dotted line: $\sigma_{abs} = 70$ mb; solid line: parametrization (6); dashed line: $\sigma_{abs} = 80$ mb.

fig.16: Quotient R as a function of the impact parameter scaled with b_{max} for the systems $Ni + Ni$, $Ne + Ni$ and $Si + Si$ at 1.85 GeV/u, 2.0 GeV/u and 2.1 GeV/u. Dots: RBUU-model; solid lines: fits according to eq. (48).

fig.17: Scalar and vector selfenergies $U_s(p)$ and $U_0(p)$ for nucleons at different densities in units of $\rho_0 \approx 0.17 fm^{-3}$.

fig.18: Invariant cross section for antiproton production in the reactions p+^{12}C and p+^{63}Cu at $\Theta = 0^o$ as a function of the antiproton momentum p in the lab. system. The experimental data are taken from ref. [11] and correspond to bombarding energies of 5.0 GeV , 4.0 GeV and 3.5 GeV. The full lines represent calculations for free antiprotons. The dashed lines indicate the result for an antiproton selfenergy of - 100 MeV at 4.0 GeV.

fig.19: Invariant cross section for antiproton production in the reaction $^{28}Si +^{28} Si$ at 2.1 GeV/u and Ni + Ni at 1.85 GeV/u for $\Theta = 0^o$ as a function of the momentum of the emitted antiproton in the lab-system. The experimental data have been taken from refs. [9] and [12], respectively. The upper lines indicate the calculated cross section for free antiprotons without reabsorption whereas the lower solid line is obtained when including $\bar{p}$ annihilation. The dashed line represents the cross section adopting an attractive potential of the antiproton of - 150 MeV.

fig.20: Invariant cross section for antiproton production in the reaction $Ni+Ni$ at 2.5 GeV/u (solid), 2.0 GeV/u (dashed), 1.85 GeV/u (dotted), 1.6 GeV/u (dotted-dashed) and 1.4 GeV/u (dotted-dotted-dashed). All calculations were done using an attractive $\bar{p}$-potential of -100 MeV at $\rho = \rho_0$. The experimental data are taken from [12].

fig.21: Comparison of our extracted values for the Schrödinger equivalent antiproton potential from p + A and A + A reactions with the prediction from the $\sigma - \omega$

model (dashed line) and the dispersive potential according to eqns. (1) - (5) (solid line).

TABLES

	2.0 GeV/u			2.5 GeV/u		
	NN	$N\Delta$	$\Delta\Delta$	NN	$N\Delta$	$\Delta\Delta$
Si+Si	5 %	45 %	50 %	10 %	52 %	38 %
Ca+Ca	6 %	46 %	48 %	8 %	50 %	42 %
Au+Au	4 %	42 %	54 %	6 %	44 %	50 %

TABLE I. Relative contributions of the different reaction channels integrated over $N_1 + N_2$.

	Ni + Ni	Ne + Ni	Si + Si
A	1.0022	1.0025	1.0122
B	0.9	0.9	0.9
C	0.05	0.04	0.06

TABLE II. Parameters A, B and C for the fit (48) of R.